Prediction of Optimum Spectrum for Full Scale Fatigue Test

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ABSTRACT

The standard FALSTAFF flight load sequence was modified by eliminating different levels of small amplitude load excursions to derive several different test load sequences. The fatigue crack growth behavior under all these spectrum load sequences were predicted in a compact tension (CT) specimen of an airframe grade structural steel. Crack growth predictions were made using a fatigue crack growth law derived from constant amplitude fatigue crack growth tests, which incorporated crack closure effects. It was observed that fatigue tests could be accelerated by using one of the derived optimum test load sequences without any significant effects of omitted load cycles on fatigue damage accumulation in the material. The underlying mechanism for the observed growth behavior is highlighted.

Keywords: Fatigue crack growth, Spectrum, FALSTAFF, Full scale fatigue test

1. INTRODUCTION

Full scale fatigue testing is one of the important steps in life extension program of an aging airframe. A representative airframe selected from the fleet of aging aircraft is loaded under spectrum sequence for a specified number of flight hours and the airframe is checked thoroughly for fatigue damages through visual and NDT methods. Repair and/or replace schemes for damaged components, if any, are then evolved based on these test results to enhance the Total Technical Life (TTL) for the fleet of aircraft.

The spectrum load sequence to be applied on the airframe during full scale fatigue testing in the laboratory is generally obtained from the flight data records of previous flights. Considering fatigue loads in various types of missions that the aircraft is used for and a statistical mix of these missions, a representative flight load spectrum block is derived. Higher the number of flight data used for spectrum derivation, more realistic the spectrum sequence would be. Such an exercise results in a block of flight load sequence, generally, containing a very large number of load reversals. Since average test frequency for loading in full scale fatigue test is kept low, the total number of reversals in the load sequence determines the testing time. One of the methods to accelerate the full scale fatigue test is to eliminate large number of small amplitude load cycles that may not cause considerable fatigue damage [1-6]. The modified optimum load sequence should contain as few a number of load reversals as possible but should have almost similar fatigue damaging effect on the airframe materials as that of the original load sequence.

In this investigation, the standard FALSTAFF spectrum load sequence was modified based on fatigue crack growth analysis. By eliminating small amplitude load excursions below a prefixed filter value, several different test load sequences were derived from the original FALSTAFF flight load sequence. Fatigue crack growth behavior was predicted in an airframe grade structural steel under all these load sequences using a crack growth model obtained from constant amplitude fatigue crack growth test data. Based on the predicted results, it is shown that fatigue test could be accelerated significantly by using one of the derived load sequence. The underlying mechanism for observed growth behavior is highlighted.

2. FALSTAFF LOAD SEQUENCE

The original FALSTAFF load sequence [7] is shown in Fig. 1. This spectrum was produced from actual flight records of the wing-root loads from four different types of fighter aircraft on a variety of missions. The data were normalized and simplified in various ways to give a uniquely defined sequence of relative loads. This one block represents 200 flights.

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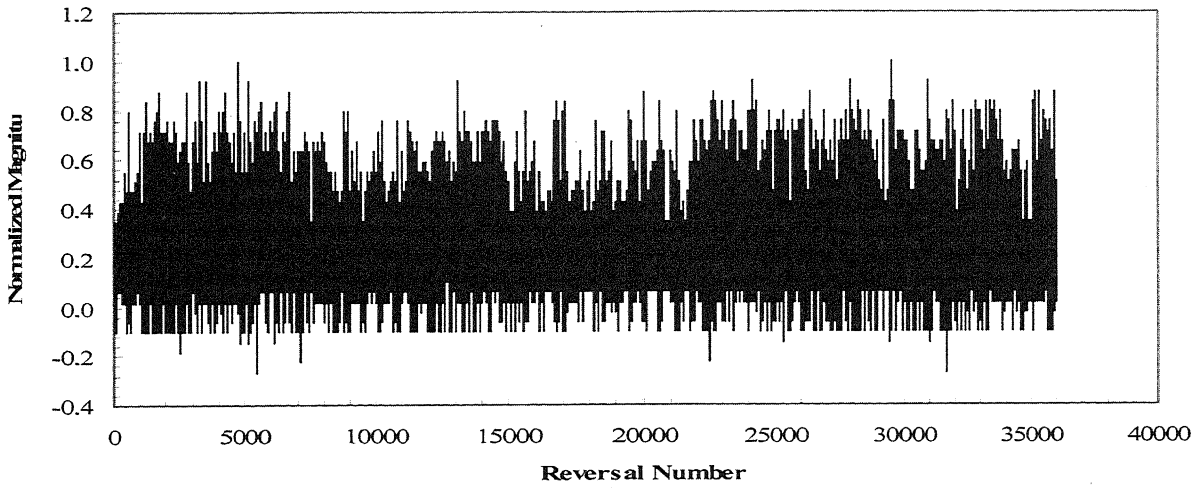

Figure 1. The standard FALSTAFF load sequence [7]

The total number of load reversals in this block is 35,966. For the sake of analysis, the maximum load, P_{ref} was set to 30 kN (corresponding to a normalized factor of 1.0) and all the other reversal points were correspondingly multiplied to obtain the load pattern.

2.1 Modification of FALSTAFF Load Sequence

Several different test load sequences were derived from the original FALSTAFF load sequence by eliminating small amplitude load excursions using a simple computer program. The algorithm used for elimination was that an upward (downward) range, smaller than the prefixed filter value was eliminated only if it is followed by a larger downward (upward) range. This procedure is applied iteratively. At first, all the stress ranges in one direction are eliminated and then, iteratively, all the ranges in the other direction and so on, until no stress ranges lower than the filter value are present in the sequence. Various load sequences derived as explained above are shown in Table 1 and a plot of derived M3 load sequence is shown in Fig. 2.

Table 1. Details of original and modified FALSTAFF load sequence n

Load sequence identification	Omission criteria (% of max. amplitude)	No. of reversals in one block	% reduction in total number of reversals
M0	None	35,966	--
M1	10	34,768	3.33
M2	15	14,631	59.32
M3	20	8,563	76.19
M4	30	5,735	84.05
M5	35	3,581	90.04
M6	40	2,855	92.06
M7	50	1,321	96.32

It may be noted that the total number of load reversals in the derived test load sequence drastically reduces with elimination of small amplitude load cycles (see Table 1). It is required to determine which of this derived test load sequence would simulate the fatigue damaging effects as that of the original load sequence, M0. The fatigue crack growth analysis was performed to determine the suitable load sequence, which would accelerate the test significantly.

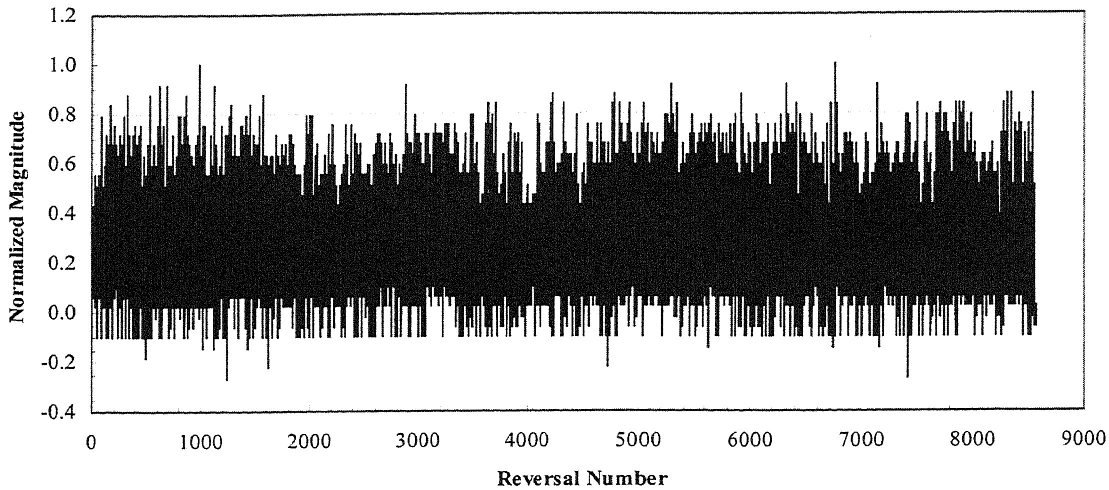

Figure 2. Modified load sequence M3

3. EXPERIMENTAL

In order to predict fatigue crack growth behavior under spectrum loading, it is required to deduce the crack growth law from constant amplitude fatigue crack growth tests. For this purpose, a structural steel was chosen which is widely used in airframe construction. The mechanical properties of the material were as follows: σ_{UTS} = 1775 MPa, σ_{YS} = 1400 MPa and elongation = 18%. Constant amplitude fatigue crack growth tests were performed using C (T) specimens of 50 mm wide and 25 mm thickness. All the tests were performed in a computer controlled, 100 kN servo-hydraulic test machine, as per ASTM E647 standard [8] at various stress ratios, R = 0.1 to R= 0.7, with a sinusoidal waveform at a frequency of 10 Hz.

4. RESULTS AND DISCUSSION

4.1 Fatigue Crack Growth Law

Results of constant amplitude fatigue crack growth rate (FCGR) tests at various load ratios in the steel under investigation is shown in Fig. 3. This plot is the crack growth rate, da/dN against closure-corrected stress intensity factor range, ΔK_{eff}.

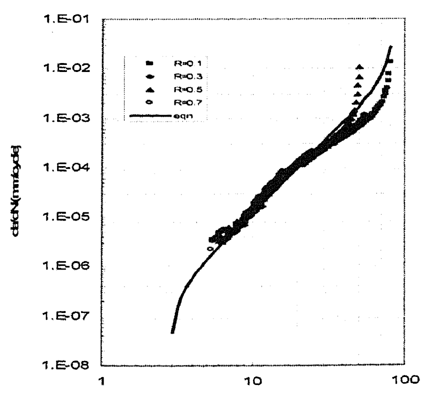

Figure 3. Fatigue crack growth rates in structural steel at various load ratios

The FCGR data in Fig. 3 was approximated in the form of Newman's [9] equation as

$$\frac{da}{dN} = C_1\left(\Delta K_{eff}\right)^{C_2}\frac{\left[1-\left(\frac{\Delta K_{eff}^{th}}{\Delta K_{eff}}\right)^p\right]}{\left[1-\left(\frac{\Delta K_{eff}}{C_3}\right)^q\right]} \tag{1}$$

The values of the constants in eqn. (1) determined from the experimental data in Fig. 3 are as follows: ΔK_{eff}^{th} = 2.9, C_1 = 1.2 x 10^{-8}, C_2 = 3.01, C_3 = 85.0, p=4.5, q = 4.3. Solid line in Fig. 3 shows the plot of eqn. (1) with these constants, which describes the entire 'sigmoidal' FCGR curve quite well.

4.2 Prediction of FCG Behavior

Fatigue crack growth in a CT specimen of the structural steel under spectrum load sequence was predicted by cycle-by-cycle approach. Adopting a constant K_{op} method [10], the amplitudes of all the cycles in load sequence above closure level was obtained by rain flow counting method [11]. The ΔK_{eff} was calculated for each of this load cycle. Then the crack growth increment for each of this load cycle was estimated from eqn. (1). A computer program was developed for cycle-by-cycle estimation of crack growth and the flow chart used is show in Fig. 4.

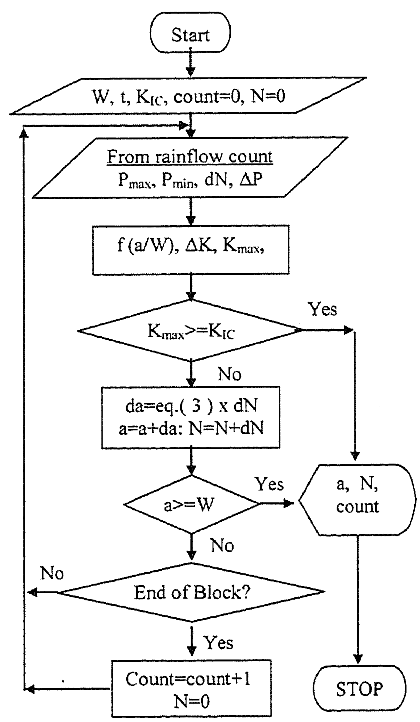

Figure 4. Flow chart for crack growth prediction

In order to validate the prediction accuracy of crack growth model, fatigue crack growth behavior was predicted in a CT specimen under original load sequence, M0 and compared with experimental results as shown in Fig. 5. Predicted behavior was almost similar to the experimental results suggesting that the model is quite accurate and can be used for predicting growth behavior under other load sequences for this material.

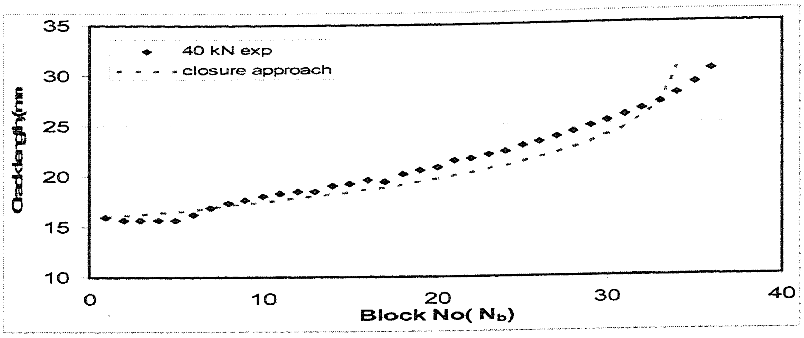

Figure 5. Comparison of predicted and experimental crack growth behavior under M0 load sequence

The predicted fatigue crack growth behavior in a CT specimen of structural steel under all the load sequences are shown in Fig. 6. The total number of blocks required to fail the specimen under various load sequences are shown in Fig. 7.There appears to be no significant difference in fatigue rack growth behavior under M0, M1, M2, and M3. However, the crack growth is delayed under M4 to M7 load sequences. The above results suggest that the small amplitude fatigue cycles (up to 20% of max. amplitude) do not have any significant effect on fatigue damage in this material.

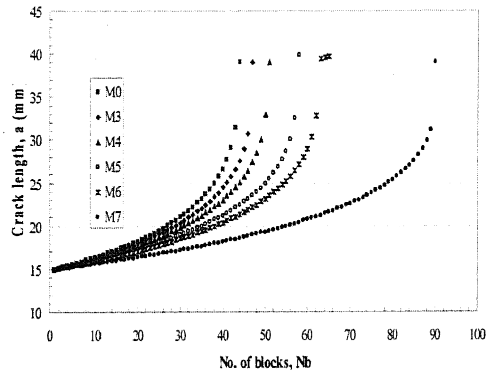

Figure 6. Predicted crack growth behavior

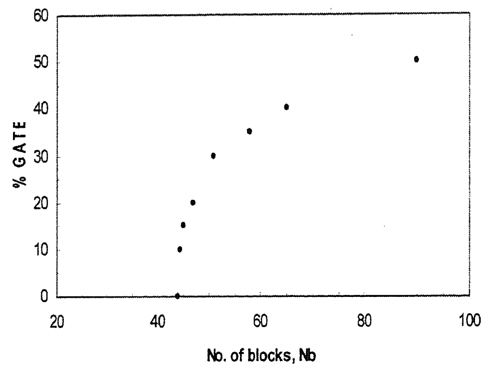

Figure 7. Predicted crack growth life

If suppose load sequence M3 is used for fatigue testing instead of original FALSTAFF, then there is significant reduction in testing time due to very less number of load reversals in M3 compared to M0 (see Table 1). It may be noted that the present analysis is based only on the fatigue crack growth behavior. In service, both crack initiation and propagation life is to be considered. Hence, a similar analysis on crack initiation should also be performed before finalizing on the optimum load sequence for accelerated fatigue tests.

The increased life under modified load sequence is due to two different reasons [2]. Firstly, the existence of small amplitude load cycles in the original spectrum sequence lower the crack closure level due to repeated compressive action leading to a smoother crack surfaces. Omission of these small amplitude load cycles result in relatively rough crack faces and hence, higher crack opening level. This in turn, decreases the crack growth rates to result in enhanced fatigue life under modified load sequences. Secondly, the life enhancement under modified load sequence results from the truncated load cycles above the opening level, which is schematically shown in Fig. 8 [2]. The crack increment under original history is $\Delta a_1 = \Delta a_{11} + \Delta a_{12} + \Delta a_{13}$ whereas, under modified load sequence, crack advance is only Δa_2 which is smaller than Δa_1.

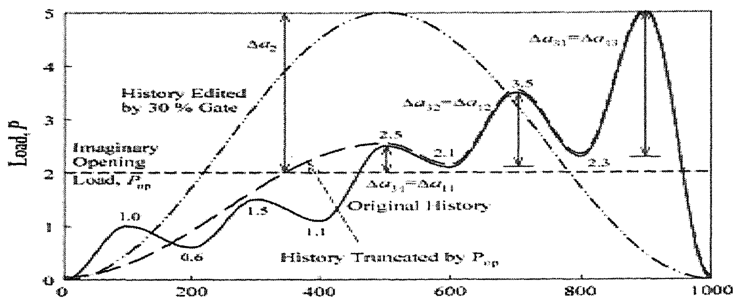

Figure 8. Mechanism of increased life under modified load sequences [2]

5. CONCLUDING REMARKS

The original FALSTAFF flight load sequence was modified to yield several different test load sequences. The fatigue crack growth behavior was predicted under all these load sequences. It is shown that fatigue test could be accelerated by using one of the derived test load sequence which has significantly lower number of load reversals but has almost similar fatigue damaging effect as that of original load sequence. It is suggested that similar studies in fatigue crack initiation should also be carried out before deciding on the modified optimum test load sequence.

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